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SIMULATION IN MODERN AERO-SPACE VEHICLE DESIGN

by

C. B. WESTBROOK

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(6) SIMULATION IN MODERN AERO-SPACE VEHICLE DESIGN,

(10) by

Charles B. Westbrook,

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SUMMARY

In this ~~Report~~ a review is presented ~~is made~~ of the simulation facilities commonly used in the United States. An attempt is made to classify these facilities and to understand how and why they are needed and came into being, and how they are used. An indication of the use of flight control system simulators in the design of a vehicle in the United States is given. Some thoughts on the philosophy of use of simulation are offered and conclusions presented.

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SIMULATION IN MODERN AERO-SPACE VEHICLE DESIGN

Charles B. Westbrook*

1. INTRODUCTION

In the design of modern aero-space vehicles the use of simulators has become more and more widespread. In this paper a review is made of the simulation facilities commonly used in the aircraft research and development process in the United States. An attempt is made to classify these facilities and to understand how and why they are needed and came into being, and how they are used. It is hoped that this collection of information, the codifications and conclusions may be of some benefit to those who use and are planning to use simulation facilities.

Before proceeding further, it is necessary to clarify what is meant by the word simulator. As commonly used by various individuals of differing interests, it has a rather widely varying definition. For the purpose of this Report, simulators are initially considered, in the broadest sense, as facilities which will allow an analog representation of a particular control element, combination of control elements or the complete flight control-airframe-pilot system. This would include simulators to obtain data on control hardware, the human pilot and his display, the airframe with elasticity, and the complete system. Classification of simulators in various ways is performed and existing facilities described. Consideration of the wide spectrum of simulators under this broad definition is useful in giving a perspective view of the subject.

Attention is then particularly directed at simulators used in the various phases of development of a typical vehicle. These phases include the preliminary design phase, the detailed design and development phase, and the experimental flight test phase.

Finally some thoughts on the philosophy of use of simulators are given and a summary and conclusions presented.

2. CATEGORIZATION AND DESCRIPTION OF SIMULATORS

There are numerous ways in which simulators can be classified or grouped. Four ways will be discussed briefly. First there is the hazy concept of computation as differentiated from simulation. Next is the grouping by type of facility. A third way of looking at simulators is by the phase of research and development in which they are commonly used. This Report is primarily concerned with simulators for use in design and development; however, it will be observed that this division does not occur very neatly. Finally, simulators will be considered relative to the element or elements of the flight control system on which they are intended to obtain information.

First, let us look for a moment at the area of simulators versus computation. In 1935, Mueller at Massachusetts Institute of Technology devised an electrical device

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Chief, Aero-Space Mechanics Branch, Flight Control Laboratory, U.S. Air Force for solving the longitudinal stability equations. In Reference 1.3, in addition to reporting the result of his work, he predicts the possibilities of extending his device to real time and even to the use of hand controls and perhaps investigation of pilot training. During World War II and the years immediately following, rapid progress was made in development and application of differential analyzers. By 1948, electronic analog computers of significance were beginning to become available. The availability of these computers made possible the development of flight control system simulators as we know them today. All major aircraft companies in the United States have large general purpose analog computer facilities ranging in size from 200 to 600 operational amplifiers. While being simulators themselves, in a sense, these analog computers are used both for general computation purposes and for connection with a cockpit and/or equipment to form a simulator.

While not a simulator by any stretch of the word, the digital computer is making spectacular progress and has made improvement possible in scientific and engineering computations. Appendix V lists the large digital computers currently in use in the United States aircraft industry. Rental on the 704 is about $12,000 per month while the 7090 rental is $43,000 per month. Utilization has to be very high to justify these expenditures. Reference 1.48 summarizes present status of use of these computers in the aero-space industry of the United States. One advanced operational flight simulator already uses a digital computer. It may well be that the availability of these powerful tools may make possible drastic improvements in simulation as they have done already in computation.

For the purpose of this Report analog computers will not be considered to be simulators and will not be discussed further.

There are a multitude of different types of facilities, all called simulators. This fact is easily appreciated by glancing through Appendices I, II, III and IV of this Report. One distinctive class is that covered by the name Environmental Simulator, a typical example of which is shown in Figure 1. Appendix III lists some of the major environmental chambers and other environmental facilities available in the aero-space industry of the United States. The smaller facilities which are so common in industry and so useful in component development are not listed. Also not listed are certain specialized facilities such as nuclear reactors, vibration and fatigue facilities, etc. (See Reference 3.23 for a much more detailed listing of U.S. government facilities).

Environmental simulators are very valuable in performing research on the particular effect or effects that can be duplicated and in determining the suitability of equipment forced to operate in these environments. Their use, size, complexity and cost have grown rapidly in recent years as new and unfriendly environments are being explored. Combinations of environmental simulators with flight control type simulators are available now to a limited degree and no doubt these combinations will increase. Although included for the sake of completeness, no further discussion of this category of simulation will be made.

The phase of research and development of aero-space vehicles with which one is concerned influences considerably the choice and use of simulators. These phases can be listed as (1) research, (2) preliminary design, (3) development, (4) flight test and (5) training and operational use. First is the research phase in which knowledge is gathered on various subjects of interest. Upon initiation of a program to design and build a vehicle the preliminary design phase is encountered followed by detailed development of the vehicle and all of its components. The flight testing phase has its special needs for simulation. Finally the phase is reached where the vehicles are in production and use and the operational commands are faced with training and with maintaining the proficiency of their crews.

Those using research and development simulators can thank the training simulator people for providing the motivation for and the development of many of the techniques and equipments necessary for what is used. Much of the past and present literature on simulation relates to this area. During the early years, World War II and somewhat before, various techniques and devices called trainers were developed to meet the vast training problems. Hundreds of millions of dollars were spent on trainers during World War II in the United States alone. Expert opinion is that this expenditure saved much over actual flight; in fact, training in flight would probably have been impossible. With the availability of analog computers in the late forties, modern training simulators became a possibility. Another factor was the development and availability of improved concepts and knowledge about servo systems and components developed in World War II, especially in Germany. Shown in Figure 2 is a modern operational training simulator. This is a large expensive device carefully designed to simulate as nearly as possible the actual cockpit environment and the characteristics of the production vehicle. As a matter of fact, however, numerous analyses have shown that these trainers can quickly save far more than they cost in reducing expensive flight time needed to maintain pilot proficiency, particularly in such areas as instrument flight and simulated emergencies.

There is no sharp line between the first four phases in the kind of simulators used. The operational trainer, because of the special needs and the special economic factors involved, has been essentially a clearly separated category. In view of the very limited production of future vehicles and their highly specialized and complicated nature, this sharp line of demarcation may not remain. However, no further discussion of this category will be made in this Report.

Simulators group themselves, to a degree, according to the element or elements of the ~~flight~~ control system about which they are to provide information. To illustrate my definition of the flight control system, consider Figure 3. This block diagram has a block representing the human pilot, a block representing the control equipment needed inside the vehicle, and a block representing the dynamic characteristics of the airframe. Simulators as used with respect to each of these system elements will be discussed.

Finally and most important of all to the system engineer, simulators to examine and evaluate the total flight control system consisting of all these elements will be discussed.

In the case of the manned vehicle all of the blocks are involved for many modes of flight. In the case of the missile or certain modes of the piloted vehicle only the control equipment and airframe blocks are involved.

In the design and development of control components such as sensors, gyros, instruments, motors, servos, etc., extensive use is made of environmental simulators or facilities which have been previously discussed.

Assemblies of the various components of, for example, the hydraulic or electrical systems are often made. In some cases these assemblies and the tests performed tend to become complex and to verge on what could be called simulation. In general, however, the inclination is to call these bench or laboratory tests unless combined with the airframe dynamics and other components.

And now for a few words on the block representing the human pilot. A great variety of simulators have been and are being used to determine man's tolerance to one or more of the environmental conditions that he may encounter. A number of these facilities are listed in Appendix III; many are not. There are centrifuges and various other devices to subject men to accelerations, air bearing platforms and water tanks to attempt to simulate zero g, and airplanes to demonstrate actual zero g. Chambers exist to subject men to intolerable noise and other chambers to impose absolute quiet. Men have been exposed to extreme cold, and in other tests roasted to high temperatures. Confinement capsules resembling cockpits and space cabins are being utilized. Simulators have been and are being used to determine the dynamic characteristics of the human pilot as a servo element, as in References 6.1 through 6.23. These simulators are of the simple fixed-base type and will be discussed a little later when considering simulators to examine the complete flight control system.

With the broad definition of simulators that has been stated many of the devices that aerodynamicists use to perform their art are included. Art is still a better word for the practice of aerodynamics than science, it is believed. In fact, somewhat ruefully, it will have to be admitted that aerodynamicists are past masters at attempting to obtain answers by simulation rather than by a thorough understanding and use of the physical laws.

With wind tunnels of all kinds very beautiful and expensive tools are available to simulate to one extent or another the actual situation. Figure 4 illustrates this point clearly, showing the vast extent of the von Kármán Gas Dynamics Facility at the Air Force Arnold Engineering Development Center at Tullahoma, Tennessee. The wide diversity and quantity of the wind tunnel facilities in the United States is summarized in Reference 1.49.

In the field of structural elasticity too, simulators are utilized. Reference 1.46 discusses a passive analog simulator of the structural and aeroelastic properties of vehicles which is currently being used in research and development by a number of groups. The distinction between calling this a simulator instead of an analog computer is a fine one.

Work is now under way under the combined sponsorship of the Flight Control and Flight Dynamics Laboratories to determine whether the wind tunnel together with appropriately designed flexible models can be used to obtain aeroelastic corrections to stability and control and structural loads. This is a much more involved simulation than normal static, rigid wind tunnel tests, or dynamic, rigid tests, or the flutter tests now run so commonly.

Another simulation tool that has specialized uses is the rocket track. Several of these rocket tracks are available and used in the United States, the longest being the 30,000 ft track at Holloman Air Force Base (see Appendix III).

To a great extent, the discussion to this point has been in the nature of giving perspective to the subject of simulation. This is important, it is believed, in understanding each other, understanding how the trend to simulation came about, and making determinations of future trends. At this point, simulators of the complete flight control system will be discussed. These, no doubt, are what many first think of when simulation is mentioned.

A bewildering variety of simulators are being used to analyze the flight control system as a whole. Figure 5 is an attempt to break these facilities down in some logical grouping. The first natural grouping is between ground-based simulators and flight simulators.

About fifteen years ago, as a result of the newly developed knowledge and ability in artificial stability and computation, an idea was born of a flight research facility which is called the variable-stability airplane. The latest versions do much more than vary the stability. In Appendix I of this paper are listed all of the variable-stability aircraft of which the author has knowledge, in more or less chronological order. The development of the concept and the increasing complexity and also capability of these aircraft can be followed by reading through this listing and the descriptions. The listing starts with the Cornell-Navy F4U-5 and reaches its high point with the present NASA-Ames F-100 and the Cornell-WADD T-33. The Air Force-Cornell T-33 has the features of variable stability, control, feel, and display and it will soon have the capability of varying the L/D ratio to simulate more advanced designs. It has the capability of varying stability and control characteristics with time such as occurs in a re-entry. It does not as yet have the ability to vary C_{L_α} without varying other derivatives. This would be a desirable addition. The T-33 can also be used as a fixed-base ground simulator by connecting it to an analog computer in its hangar.

In the area of V/STOL variable stability aircraft, NASA at Ames has made a limited variable-stability installation in an X-14 aircraft and an installation for a YHC-1A helicopter is being made for NASA at Langley. There is certainly much important handling-qualities research that could be done by a suitable installation in a VTOL aircraft with an adequate payload capacity.

Being such a realistic simulator when properly done, the variable-stability aircraft is a most valuable research tool. It is also valuable in evaluation of preliminary design concepts and in training and indoctrinating flight test pilots. The concept has been proposed for use in operational trainers. Enthusiasts have even proposed a universal trainer using variable-stability ideas. Such thinking does not recognize the practical limitations and difficulties that exist. There may be certain possibilities in this idea for the future, however.

Experience has shown that, in common with most flight tests, use of these airplanes for research and development is expensive and time consuming for each data point obtained. In the opinion of the author the most suitable usage of these airplanes is to make final checks and correlations of data points that have been explored as well as possible in ground simulators. (See Appendix VI for extensive references to variable stability aircraft).

Figure 5 divides the ground-based simulators into groups according to the motions that can be imparted to the pilot: no motion, rotations, translations, and combinations of rotation and translation. In Appendix II are listed various flight control system simulators that are available. This listing is certainly not complete. The class of simple cockpit-analog computer simulator that is so common in the industry and the various research organizations has been excluded.

The majority of the fixed-base simulators, and the motion simulators as well, use instrument displays; these range from simple scope or dial instrument type displays to elaborate display simulators such as the WADD-F-102 simulator modified for general purpose display research. External display simulators are becoming more common, usually for approach and landing studies, VTOL investigations, and in a few cases to simulate space environment.

The complete mission of an orbital vehicle has been simulated by Chance Vought. Included is simulation of the six-degree-of-freedom flight mechanics and the orbital flight, re-entry, and landing. A 560 amplifier analog computer and a digital computer are required to perform this simulation.

In a few cases an attempt to simulate acceleration has been made by pulling on the shoulder straps or exerting pressure on the seat cushions. This is indicated by the 'pseudo G' block of Figure 5. The worth of this feature in improving correlation of data with actual flight is not known.

It has become standard practice in aircraft and missile development to make use of a category of simulator that is called the 'iron bird' or the 'iron monster'. This category is of great importance in the design and development process. The first step in the development of an 'iron bird' is normally the use of a simple cockpit-analog computer simulator as shown in Figure 6. This particular simulator is a Republic Aviation Corporation installation. Another typical installation, in Figure 7, belongs to Grumman Aircraft Engineering Corporation. Simulators such as this can be quickly built up and adapted to the problems of the particular mission and configuration by connection with the analog computer facilities that are available in all companies.

As the design of the vehicle progresses and components of the control system are designed and begin to be available, the 'iron bird' simulator is built. A typical installation is shown, in Figure 8, of the Douglas A4D-2N. Normally, these simulators go through a continuous refinement process all through the years of development, starting with little actual equipment, then insertion of early components and then the production hardware. The cockpit also normally shows such a growth starting with simple controls and presentation and finally, in some cases, a very complete mock-up. The actual vertical tail of the A-4D is shown installed in the photograph. This procedure is followed in some cases where it is felt that structural elasticity effects are necessary to provide adequate simulation.

The simulation of the aerodynamic characteristics also undergoes continuous revision as knowledge of the airplane grows with analyses and wind tunnel tests.

Figure 9 shows another example of this type of simulator. This one is of the North American X-15 and can properly be classed as an 'iron monster'

In certain cases of extremely complex systems a second partial 'iron bird' may be built to obtain reliability and qualification information on the system and the components in addition to the system performance information normally sought on the 'iron bird'

In some cases a final stage of simulation would be to connect the actual airplane system with analog computers to prove the performance. Figure 10, taken from Reference 1.47, shows such a simulation being performed by General Electric engineers on the F-106A automatic flight control system.

The 'iron bird' concept is not only used with manned aircraft. It is also used and endorsed by the missile designers, both aerodynamic and ballistic.

Referring back to Figure 5, let us pass on to a brief discussion of the various motion simulators in use. Very few, if any, simulators are now available with only one rotational degree of freedom. Depending on the intended function of the simulator, two or three rotational degrees of freedom will normally be incorporated. An example of two rotations is the NASA pitch-roll chair. A number of three-rotational-degree-of-freedom simulators have recently come into being, motivated basically by interest in space vehicles, VTOL configurations, and reaction controls. Many of these devices utilize air bearings and in some cases they are quite elaborate. NASA at Lewis has a four-gimbal type simulator in which high spin rates are possible.

The rotation simulators of the Link trainer type have limitations on the rotational travel. By incorporating initial motion into the simulator and then 'washing out' the motion in actuality but continuing it on the instruments, what is said to be a very effective simulation of continuous motion is obtained. This capability is incorporated in the WADD-T-37 general purpose simulator and is referred to in Figure 5 as 'pseudo motion'.

Centrifuges, as is known, have been used to produce steady g forces on pilots to determine their tolerance and capabilities while enduring these forces. At the Naval Air Development Center at Johnsville, Pennsylvania, a facility is available which combines a centrifuge with a piloted capsule with two rotational degrees of freedom. Much interesting work has been done on this facility with respect to the X-15 program.

An interesting facility for simulating zero g has been built at Lockheed, Marietta, Georgia. This facility, which is described in Reference 3.13, simulates zero g by spinning a man submerged in water about his longitudinal axis.

The only simulator known to the author which has just one translational degree of freedom and no rotational freedom is the g seat at Convair, designed to study turbulence at low altitudes. Normally, if translational degrees of freedom are included, some rotational degrees are also included such as on the pitch-heaving g seats available at NASA, Langley and North American, Columbus.

Grumman has a unique facility which incorporates pitch, roll and heave. It has both external and internal display and incorporates 'wash out' to simulate large motions. It is especially useful for VTOL, low altitude flight, and approach and landing studies.

A large simulator is available at Bell, Dallas for studying VTOL problems. This simulator has a three-degree-of-freedom cabin mounted on a strut. This strut can be moved up and down to provide heaving to the cabin and also can be moved in the other two directions to provide a corrected vertical acceleration as the cabin is rotated.

NASA, Ames has a six-degree-of-freedom simulator under design which will have a three-rotation cabin able to translate to a limited degree in all three axes. This would be intended for V/STOL and approach and landing studies.

Most impressive of all is the NASA-Ames facility having a three-rotational-degree-of-freedom cabin able to translate vertically, mounted on a centrifuge.

To provide the various motions to the simulators as discussed, results in additional complexity and cost so that, in general, as we move from left to right in Figure 5 the problems of constructing and operating the simulators are increased.

The purpose in adding these motions to the simulators, of course, is to add fidelity to the simulation, improving the correlation with actual flight. Unfortunately, this correlation is in a very imperfect stage and the answer to what is the minimum motion to provide acceptable fidelity of simulation is not available.

It is quite possible for motion of one sort or another introduced into a simulator, while being impressive to see, to do more harm than good as far as giving results comparable to the flight situation. The work at NASA, Ames reported in several references is most valuable in this respect and additional work is certainly urgently needed.

3. TYPICAL USE OF SIMULATORS IN WEAPONS SYSTEM DESIGN

At this point, it is desired to indicate what would be typical use by a United States aircraft company of simulators during the development cycle. In Figure 11, the three phases of primary interest to the aircraft company are shown in the center. As an example a high-performance vehicle of complex nature somewhat extending the 'state of the art' is assumed.

During the preliminary design extensive use of the simple cockpit simulator would be made to firm up design requirements and to give information on specific problem areas not sufficiently covered by general research programs. Considerable variation in the extent of these programs would be caused by the mission and configuration. For instance, at the present time this phase of simulation would be considerably higher if a VTOL fighter were under consideration than if a more conventional fighter were in design. As is no doubt obvious, both the kinds of simulators used and the types of programs conducted are very similar to those in the research phase. Variable-stability aircraft can be and have been of use in examining particular problem areas of specific designs not sufficiently understood.

In the detailed development phase heavy emphasis is laid on the 'iron bird' simulator. In a not too sophisticated system most of the effort may be placed on the equipment development and proof testing. Preliminary exposure of the flight test group to the characteristics of the system will be provided in order to allow proper planning of the flight test program.

In view of the elaborateness of the 'iron bird' simulator considerable expense is involved in both constructing and operating it. However, its use is universally endorsed by the industry, with no exceptions to the knowledge of the author, as a time and money saver. Basically its use is a function of the complexity of the design, the degree to which the design is pushing the state of the art, and, related to the first two, the dollar cost of the system. With the tremendous cost of bringing a design to the flight test stage, the fantastic cost of flight test time, and the horrendous economic waste caused by mistakes, miscalculations and redesign, the 'iron bird' is felt by all to be an essential.

As the aircraft progresses into the flight test stage increased emphasis may again be placed on the cockpit simulator. The dust may be brushed off the simple simulator and it may be improved to demonstrate dangerous conditions to the pilots and to guide the test program. The 'iron bird' is utilized in evaluating the final equipment to be used in the production aircraft.

If the particular design is conventional both in aerodynamic configuration and its control system and is of relatively low performance, simulators may not be used. A judgment that they are not needed would be based on the economic factors referred to previously and to what could be called a 'confidence factor'. This 'confidence factor' is a function of how sure the engineers are of their knowledge and theoretical calculations. Such cases with a high 'confidence factor' will be very few in the future.

At the other extreme are the designs which push the state of the art to the extreme, such as the X-15 and Dyna-Soar. In these cases research type information is needed and will be gathered through all the phases indicated. Extremely complex simulation can be easily justified on the basis of the high cost of the total system. Much of the equipment is necessarily of high performance or of new design and consequently needs much simulator evaluation. Pilot training needs are much greater than normal. In view of the research nature of many such vehicles the operational use phase merges into the normal flight test phase with resulting readjustments in the consideration of flight test and operational training simulators.

4. PHILOSOPHY OF USE OF SIMULATION

And finally, before closing, a few general thoughts are set forth on the subject of simulation, in particular, flight control system simulation.

Fundamentally, simulators are used where basic knowledge is weak, complex interrelationships are not fully understood and calculations, estimates, or judgments are not trusted. In other words the confidence factor referred to previously is low. Also involved are the economic factors. With a modern complex weapon system the costs of carrying a design through the flight test phase may be a billion dollars. Furthermore, there may be no extensive production as such to eliminate the 'bugs'. Under such conditions major errors and deficiencies are intolerable. The use of simulation is affected by the philosophy of development of new aircraft in a country. Rapid exploitation of the state of the art invites the 'cut and try' approach. Such a philosophy has been followed in the United States, most exemplified by the research series of aircraft. If the development of new types of aircraft proceeded at a slow steady pace research would normally be properly accomplished prior to initiation of the design and a designer would not have the compulsion to use such extensive simulation. This rapid pace of development application of knowledge however has become a way of life and it is not believed that it will change under present conditions.

From the above factors a continual and increasing trend toward complex simulation can be predicted. There is a very real danger involved, however. Simulators are not only costly in dollars to build and operate but, more importantly, they are costly in technical talent to operate. Technical talent of high grade is not plentiful and if too much is tied up in work related to simulation, to the detriment of analytical studies and planning, the consequences can be serious.

Most serious of all is the type of attitude that sometimes develops, to simulate without thinking. This is deadly. It results in blind repetitive programs of little real worth. It is the opinion of the author that in Europe this condition is less prevalent than in the United States. Lack of a simulator may encourage the development of a more basic understanding of a phenomenon.

This is not to imply opposition to simulation. On the contrary, rather is it a plea for its intelligent use.

Another thought related to the above is with regard to the organization of simulator groups. It is the author's feeling that simulator groups many times tend to look on the simulator facility as their goal and try continually to develop and improve it whether it is needed or not. It appears much preferable for an organization to be problem orientated, having and using simulators as necessary to solve their problems.

5. CONCLUSIONS

In the preceding discussion an attempt has been made to give some perspective to the subject by classification of simulators in various ways, a review of various facilities available in the United States, and some historical background is given. Discussed in more detail were flight control system simulators, particularly the 'iron bird' type used extensively in development. An indication of the typical use of simulators by a United States aircraft company was made. Finally some notes on the philosophy of use of simulators were made.

In closing, it can be stated that simulation is a tool, use it as such and do not let it use you.

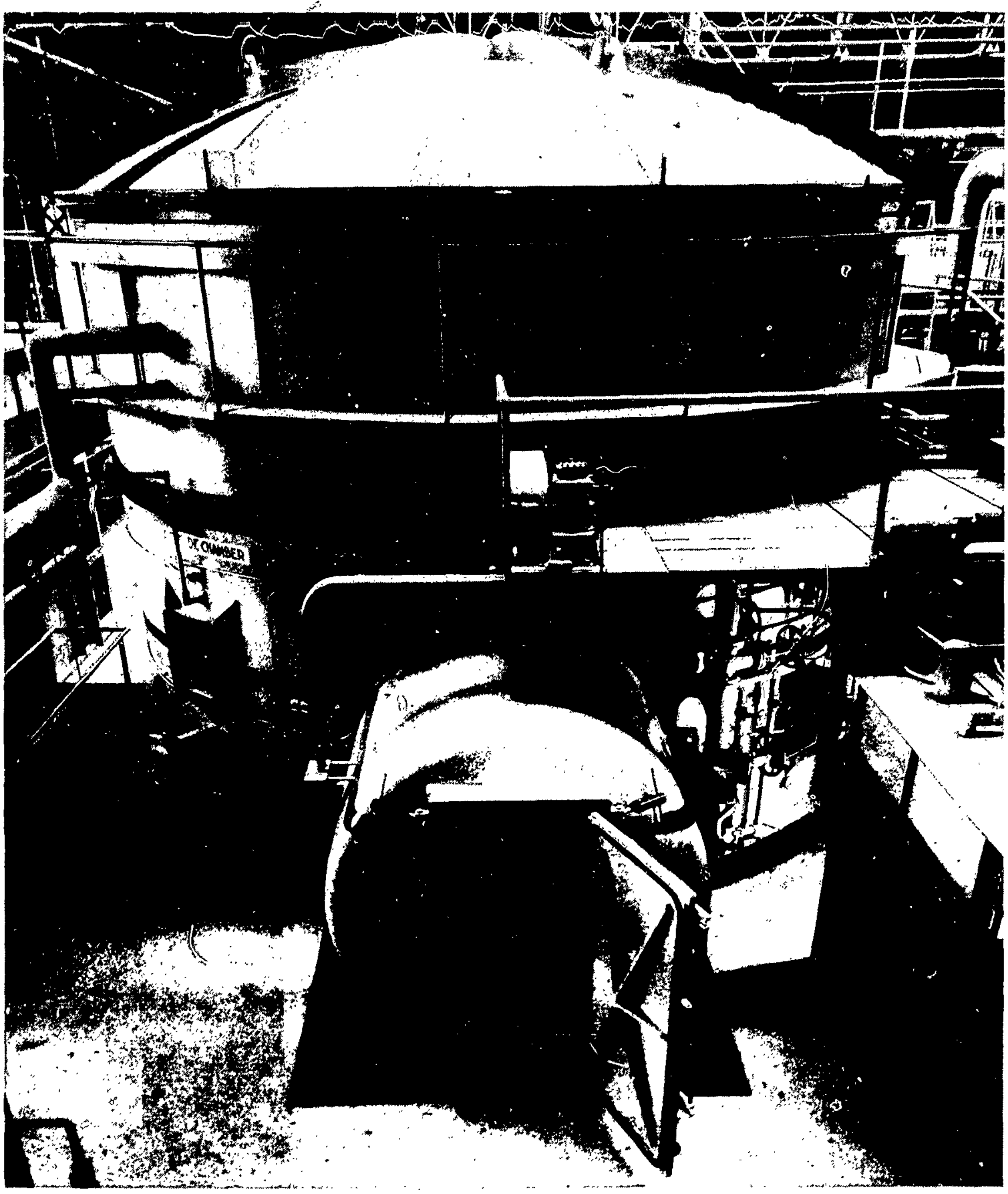

Fig.1 Environmental simulator

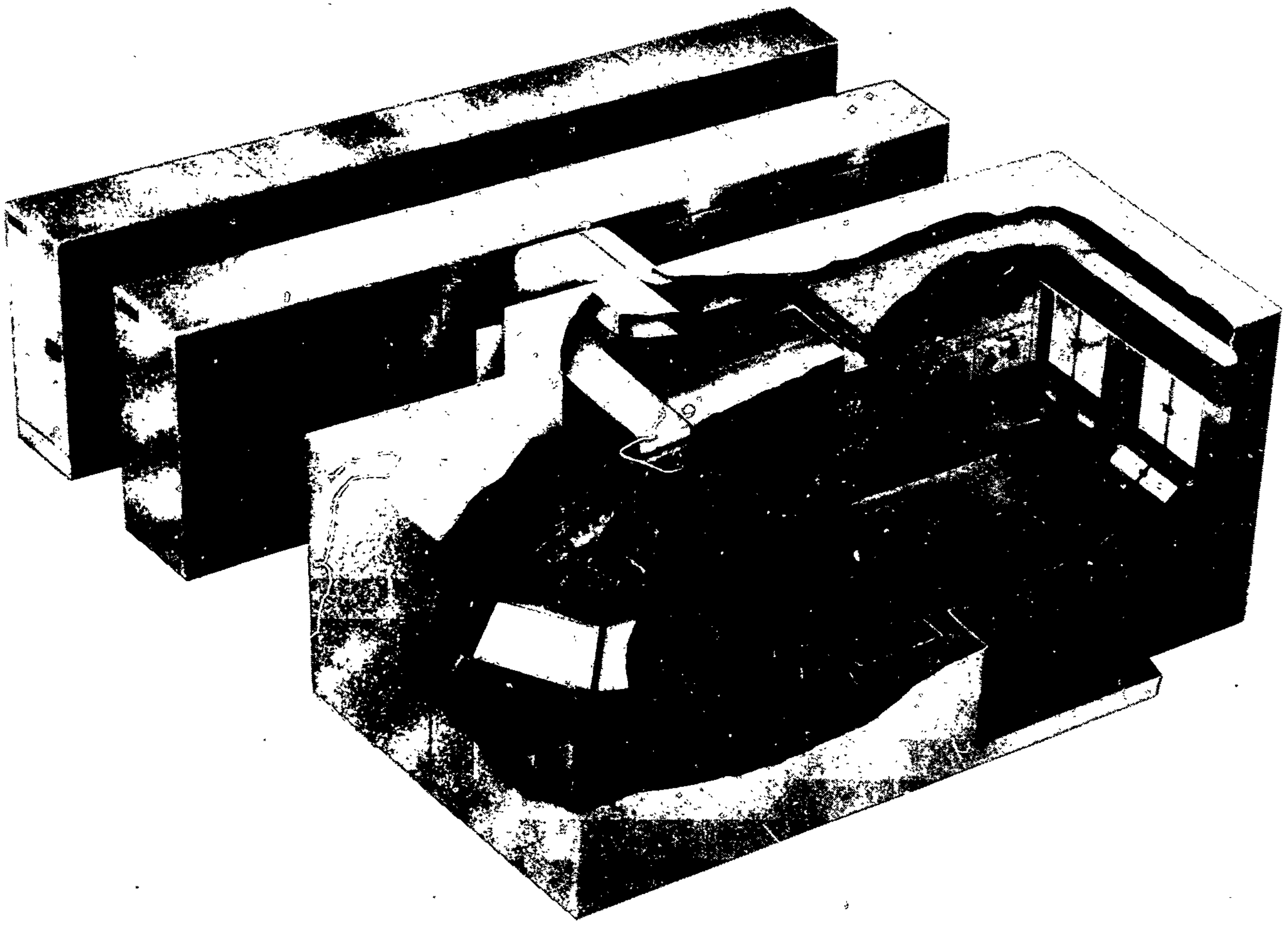

Fig.2 Operational flight simulator

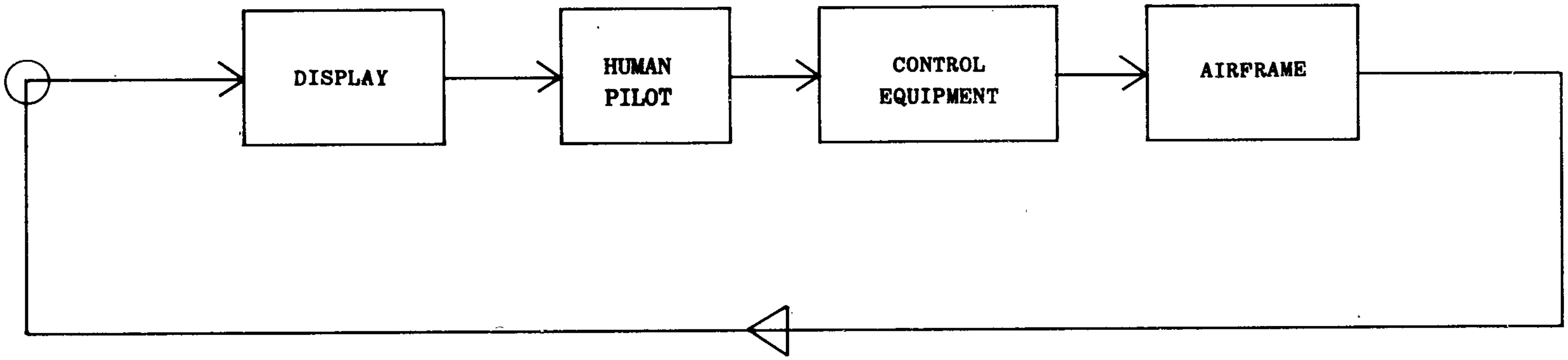

Fig.3 Block diagram - flight control system

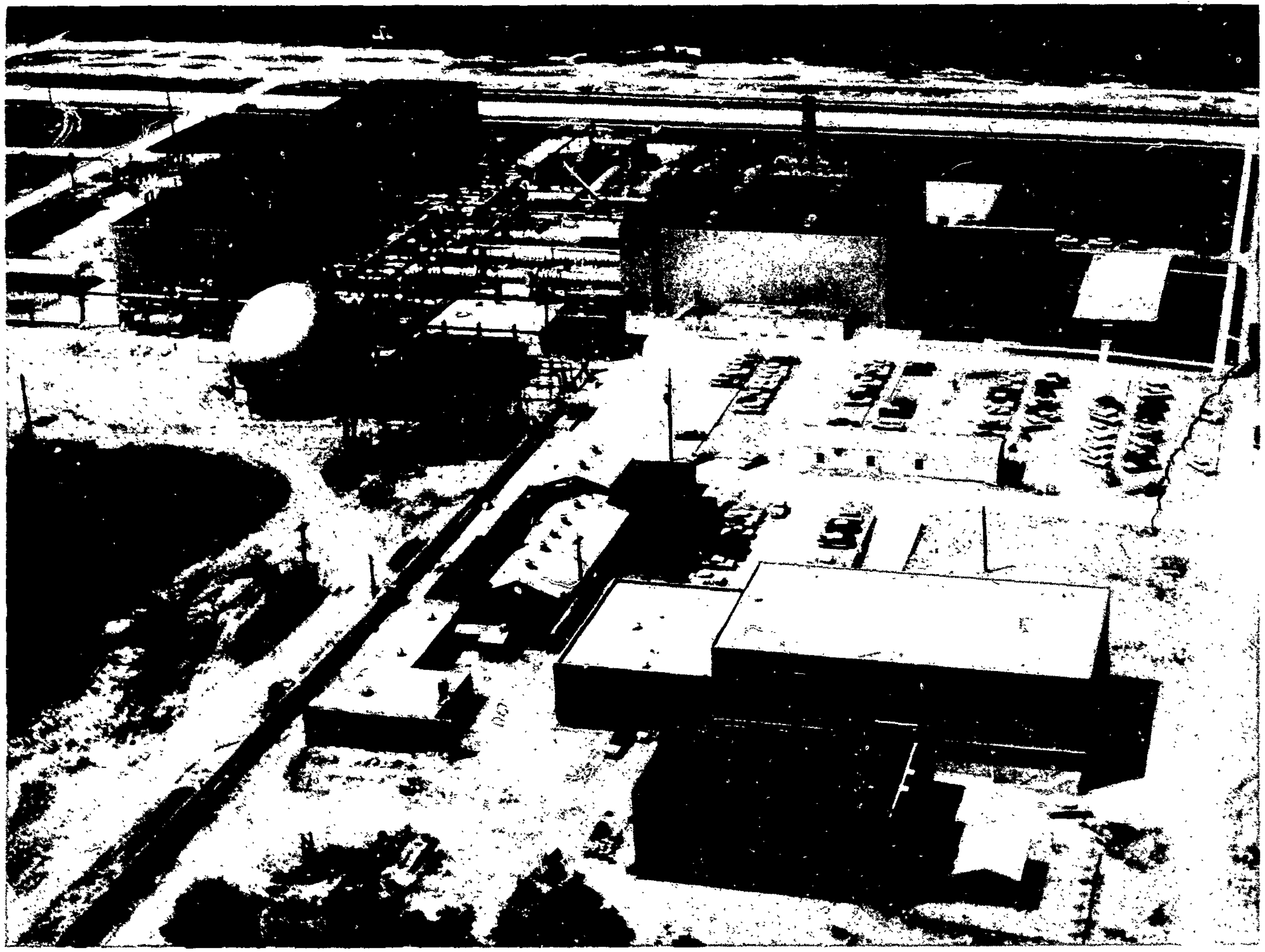

Fig.4 von Kármán Gas Dynamic Facility

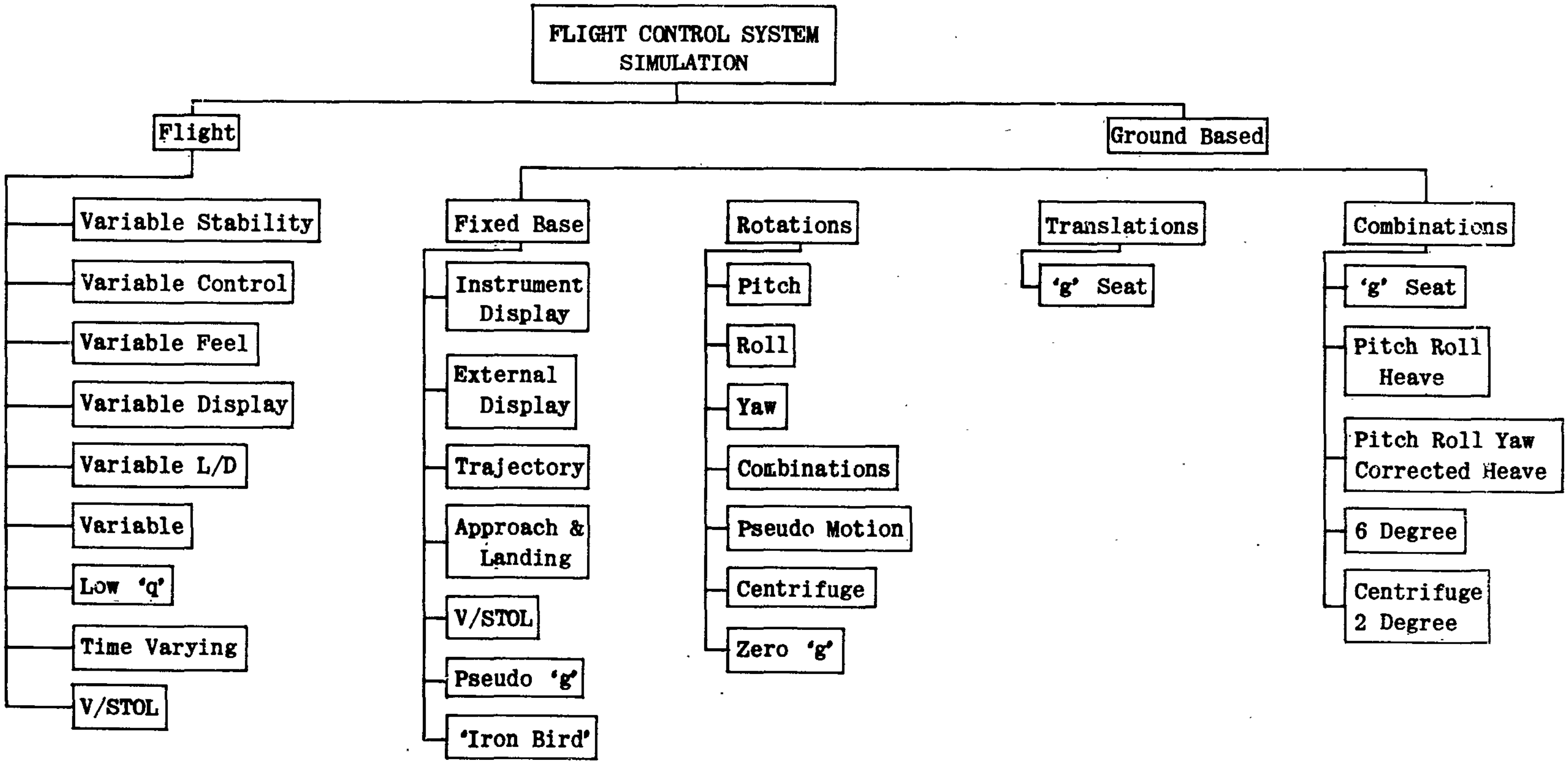

Fig.5 Flight control system simulation

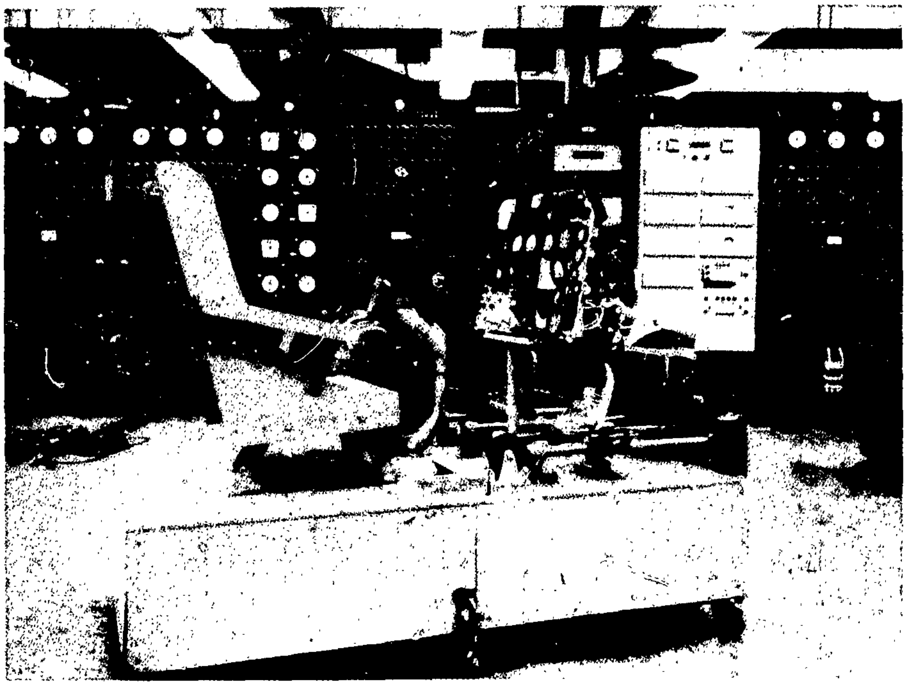

Fig.6 Republic simple cockpit simulator

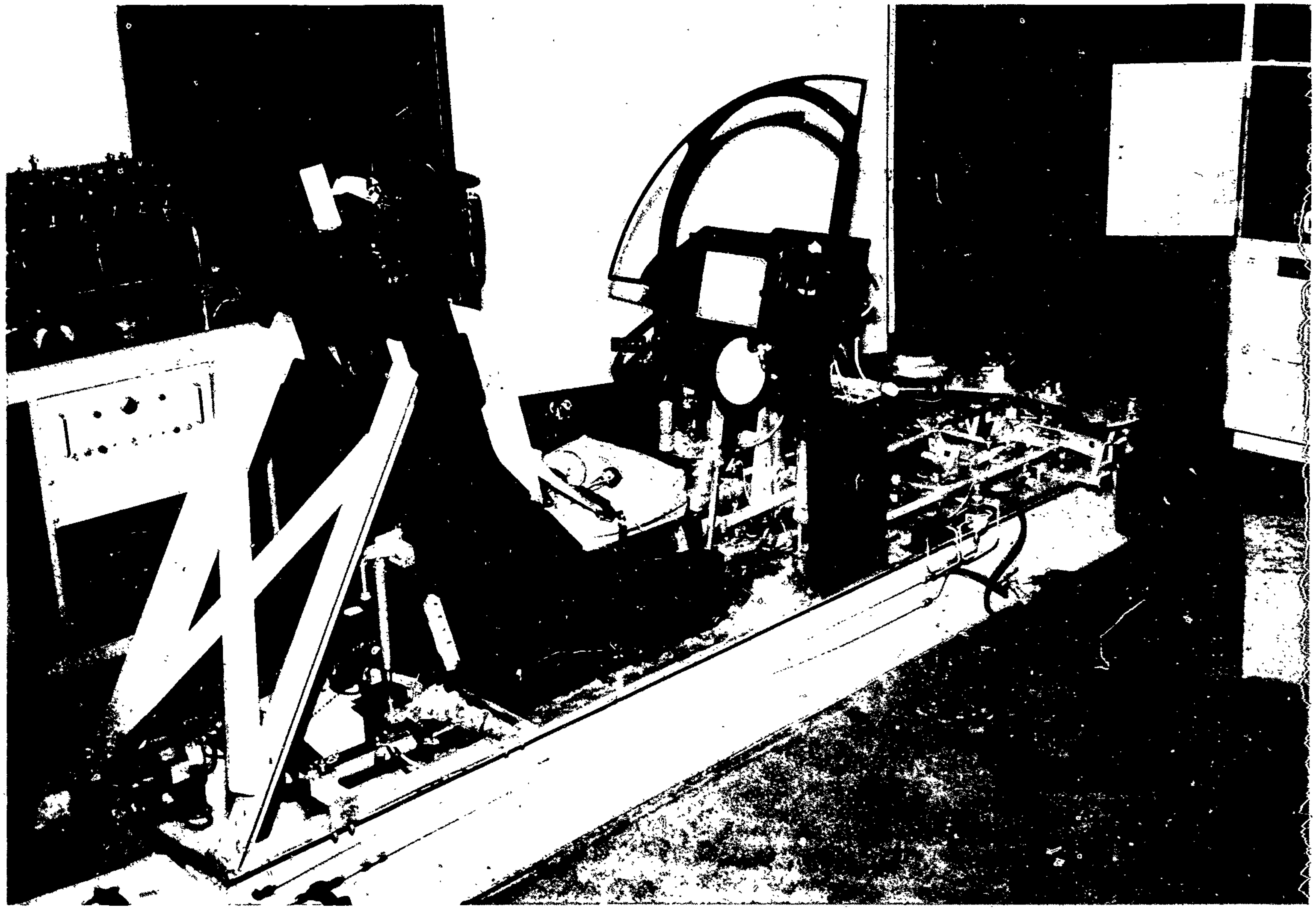

Fig.7 Grumman simple cockpit simulator

Fig.8 Douglas A4D 'Iron Bird'

Fig.9 NAA X-15 'Iron Monster'

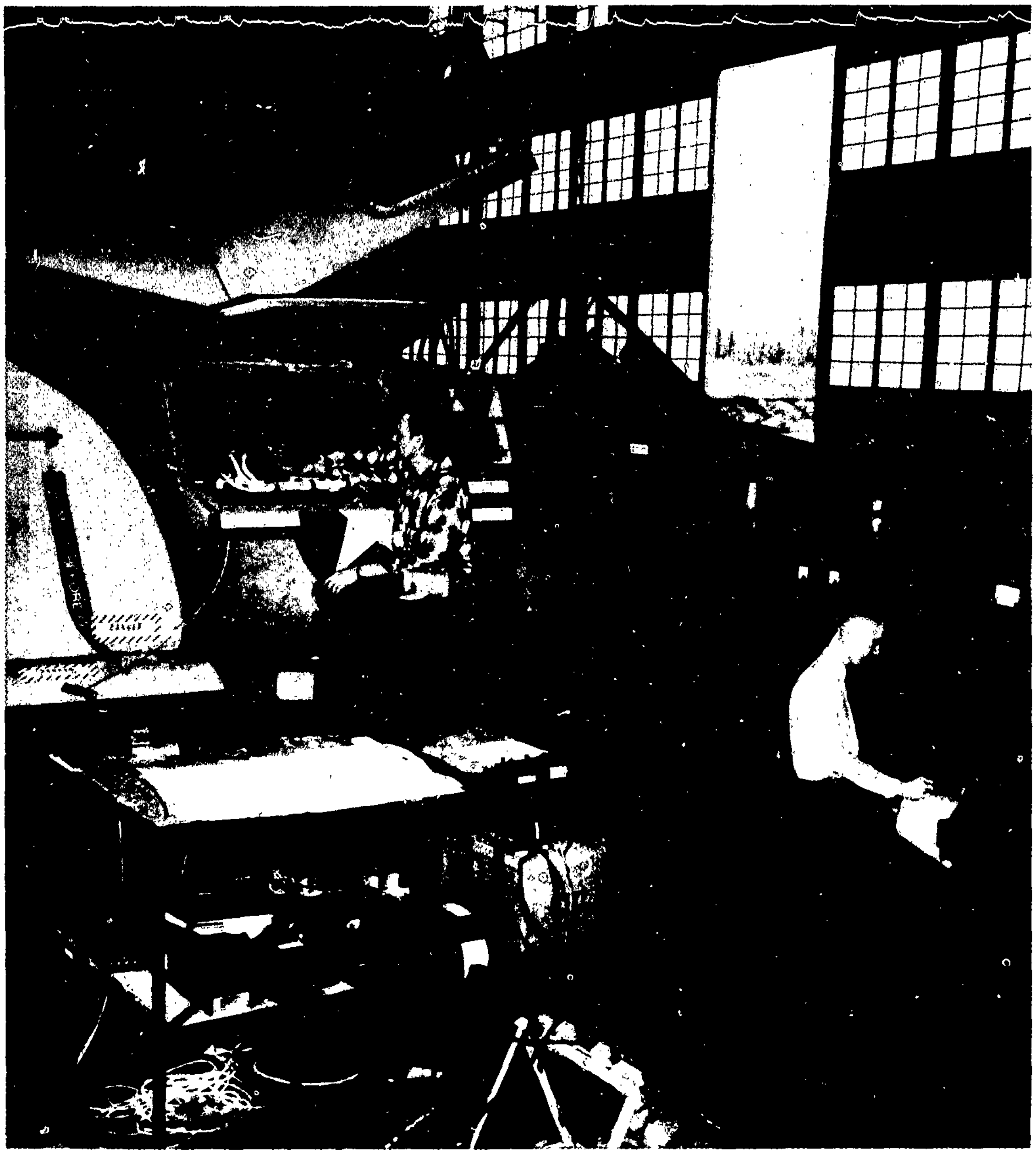

Fig.10 GE F-106A simulator

	Design requirements Data on specific problems	Final design requirements Proof of design acceptability Equipment development Pilot training	Pilot training Pilot proficiency Dangerous regimes Resolution of problems	
Research	Preliminary design	Detailed development	Flight test	Operational use
		Time		

Fig.11 **Flight** control simulator use in design cycle

APPENDIX I

VARIABLE-STABILITY AIRCRAFT

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
F4U-5	1948-49	Servomechanism system of the autopilot, fed with electrical signals from sideslip and yawing velocity pickups, deflected auxiliary rudder. Simulated changes in directional stability and damping in yaw. Periods from 1.5 to 5.5 sec. (Refs. 2.2 and 2.4).	Obtain pilots comments on a large range of aircraft dutch roll frequencies and damping in order to justify or revise many handling qualities requirements.	A proposal for Navy handling qualities requirements as a result of these tests was 'The Lateral-Directional Oscillation shall always lose at least 40% of its amplitude during each cycle following a disturbance.'
PT-26 (WADC-Cornell)	1949-50	Stabilizer incidence adjustable in flight to large negative values. Airplane would maintain steady state glides at angles of attack as high as 28°. Angle of attack at the peak of the lift curve peak 15°. Manual means used to prevent wing roll off. In later tests an autopilot used. (Refs. 2.3 and 2.11).	Project purpose was to obtain both static and dynamic data pertaining to the longitudinal motions of an airplane at angles of attack covering both stalled and unstalled flight.	Static data obtained in trimmed power-off glides. Qualities determined were pitch angle, angle of attack, normal acceleration, longitudinal acceleration.

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
B-17 (WADC)	1951-52	Conventional autopilot was connected to a force wheel. This wheel fed in a signal to the autopilot through strain gages on the spokes of the wheel, and on the pedals. Final arrangement was such that a small force commanded bank angle while a force over 3 pounds commanded aileron displacement (or roll rate). (Ref. 2.8).	Purpose of this work was to investigate the possibility of the pilot controlling the autopilot rather than the aircraft direct. Provided better stability characteristics and smoother control without adding additional force.	Use of force wheel control, in conjunction with inboard stabilization of airframe dynamics, made simultaneous flight path stability and control realizable.
C-45F (WADC-Cornell)	1951-53	Provided continuously variable artificial inputs proportional to yaw velocity, sideslip, rate of change of sideslip and yaw acceleration to the rudders; yaw velocity and roll acceleration to the ailerons; and rate of change of airspeed to the elevator. Artificial force feel on all three controls is provided with continuously variable force gradients. (Refs. 2.5, 2.7 and 2.9).	Purpose was to make all the natural modes of the airplane's motion non-oscillatory and convergent. Automatic turn co-ordination within a practical degree of accuracy was to be provided.	Essentially dead beat Dutch roll and phugoid were accomplished. (Limited pilot evaluation)

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
B26B (Cornell WADC)	1951-57	An artificial longitudinal stability and control system was installed to provide extreme variations in the following parameters; short period mode frequency and damping, phugoid mode period and damping, and control force and position needed to trim and maneuver. Short period f = 0.2 to 0.6 cps I = 0.15 to 1.2 Phugoid I = 0.15 to 0.60 f = 0.01 to 0.5 cps (Refs. 2.13, 2.14, 2.15 and 2.22).	Purpose of this program was to determine in flight the optimum and minimum flyable characteristics of bomber type aircraft.	Consistent pilot ratings of various values of short period frequency and damping ratios were obtained.
Navy T-33 (NASA-Langley)	1952-53	Variable damping in yaw was obtained by a flap-type control surface fitted to a fixed fin called a nose fin located on the forward part of the airplane. (Ref. 2.27).	Flight investigation of the effects of varied lateral damping on the effectiveness of a typical high speed fighter airplane as a gun platform.	Results of simulated strafing runs indicate that the gunline dispersion could be expected to be decreased about 7% by increased lateral damping and to be increased about 85% by decreased damping.

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
F86A (NASA-Ames)	1952-54	This variable-stability servomechanism operated in essentially the same manner as the F6F-3 equipment except the rudder and rudder tab were driven automatically and the primary power used was hydraulic rather than electric. Range of the stability derivatives were: C_{n_β} 0.50 to 0 C_{n_r} 0.38 to -1.6 C_{n_p} 0.34 to -1.0 C_{l_β} 0.074 (normal) C_{l_p} 0.385 (normal) $C_{n_{\delta_a}}$ 0.016 to 0.104 $C_{l_{\delta_r}}$ 0.0155 (normal) (Ref. 2.20).	Same as F6F-3 but higher speed range.	Simulation of higher performance prototype aircraft. Periods appear to have run from 1.0 to 1.6
F6F-3	1952-56	Variation of the stability derivatives through servo actuation of the ailerons and rudder were obtained. The stability derivatives ranges were as follows: C_{n_β} 0.079 to -0.002 C_{n_r} 0.143 to -0.306 C_{n_p} 0.250 to -0.151 C_{l_p} 0.125 to -1.02 C_{l_β} 0.048 to -0.350 $C_{l_{\delta_r}}$ 0.118 to 0 $C_{n_{\delta_a}}$ 0.007 (normal) (Refs. 2.10 and 2.20)	Simulation of prototype aircraft in order to define the ranges of acceptable characteristics which could be used as design criteria. Pilot opinion of lateral oscillatory characteristics relative to current flying qualities were considered.	Flight experience was obtained which in most cases directly applied to particular flying qualities problems associated with individual prototype development programs. Aircraft also used in simulating tracking in rough air.

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
F94A (WADC-Cornell)	1952-58	Artificial longitudinal stability and control systems were installed to provide extreme variations in 1. Short period mode frequency and damping. 2. Phugoid mode period and damping. 3. Control forces and position needed to maneuver and to trim. 4. Control breakout forces. Short period f = 0.7 to 1.15 cps I = 0.25 to 1.75 (Refs. 2.13, 2.26 and 2.28).	Purpose of this program was to determine in flight the optimum and minimum acceptable characteristics of a fighter aircraft. (Associated with B26 work).	Similar to B26.
H-5 Helicopter (NASA-Langley)	1952-58	A single rotor helicopter was outfitted so that the damping in roll, yaw and pitch could be varied by means of electrical components. The components were actuated by the rear cyclic stick or rudder pedals as well as by signals proportional to rate of roll, yaw or pitch (signals proportional to helicopter attitude were also available but were not used in the tests.) (Refs. 2.19 and 2.32).	An investigation of helicopter damping as it effects flying qualities.	Variations of flying qualities with increased damping in roll yaw, roll and pitch. Results indicate that increased damping can improve the accuracy of maneuvers and reduce the effort required of the pilot.

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
Navion (WADC-Princeton)	1952-54	Bob weights and springs, etc. to vary longitudinal dynamics. (Ref. 2.47).	Investigate effects of these devices on longitudinal dynamics	Demonstrated flight characteristics involving degeneration of short period and phugoid into other dynamic modes.
XF88A (WADC)	1954	The variable-stability system basically consisted of aileron and rudder servos actuated by sideslip, yaw, and roll rate inputs. Dutch roll oscillations were induced by rudder kicks in straight and level flight. (Ref. 2.12).	To fulfill the need of improved specifications on rolling motion. Examples - amplitude ratio of roll angles to yaw angle or roll angle to sideslip etc. Establish a tolerable intolerable boundary surface, for flight with auxiliary equipment inoperative.	Periods from 1.00 to 2.555 were accomplished.
F86E (WADC-Cornell)	1954-55	A non-linear yaw damper was added to the rudder with the servo driving the rudder direct. An artificial rudder feel system using dynamic pressure and a spring was used to simulate the normal airplane feel. The yaw damper was set so that sensitivity was left high for small sideslip angles around zero. (Ref. 2.17).	To make the rudder motion not only proportional to yaw rate but also to yaw rate as it varies with sideslip. With this equipment it was hoped that in a dutch roll oscillation, the aircraft would return to center swiftly but be damped well near center.	Tracking aim errors with this system were reduced to about two-thirds the value experienced with the normal airplane with damping of the dutch roll to around 70% of critical (I = 0.7).

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
F9F-2 (NASA)	1954-55	Two types of automatic pilots were used; one of these was of the attitude type and the other was of the rate type. With the attitude automatic pilot control system, two-types of stick force feel were used, spring feel and damper feel. Motion of the stick generated an electrical signal proportional to its deflection. (Refs. 2.18, 2.44, 2.45 and 2.46).	A flight investigation to obtain experimental information on the handling qualities of a fighter airplane controlled through an automatic pilot control system.	The pilot liked the characteristics provided by the damper force feel system much better than those provided by the spring feel system. The flying qualities of the airplane with the rate automatic pilot control system was very good.
T-33 (WADC-Cornell)	1954 to present	Irreversible hydraulic power controls are used to drive the control surfaces. This system is also designed for research in the field of design of cockpit controls. The basic system which was limited to steady state or quasi-steady state flight conditions has been supplemented by a device which permits changing of stability derivatives as a function of time for a predetermined flight path. Also it is possible to link the airplane to a computer to convert it to a ground simulator. An L/D variation device is being added.	This aircraft was initiated in order to increase the effectiveness of research work on the problems that are continually arising in the field of airplane stability and control (handling qualities). One of the revised purposes of this aircraft is for carrying out a systematic investigation of the re-entry task.	Continual development and revision over a period of several years of this aircraft has brought about a flying simulator which can duplicate the characteristics of almost any aircraft under any conditions.

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Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
T-33 (cont'd)		ω_{n_d} = (less than 0) to 1.5 cps I_{n_ϕ} = (less than 0) to 0.6 $\omega_{n_{s.p.}}$ = (less than 0) to 1.5 cps $I_{n_{s.p.}}$ = - 0.1 > I > 1.5 Phugoid period 25-200 sec I_p = - 0.20 to 0.60 (Refs. 2.16, 2.21, 2.23, 2.35, 2.36, 2.37 and 2.38).		
YF86D (NASA-Ames)	1956-58	By use of a control system stabilizer, position was commanded thru a servo system by stick force. The breakout force, system time constant, and system gain (i.e. stabilizer angle per unit stick force) could be varied over a wide range. Aircraft dynamics were varied by change in altitude and speed. Short period f = 0.63 & 0.57 cps I = 0.21 & 0.36 breakout force 0 to 25 lb time constant 0 to 4 sec static force gain 1°/pound to 0.04° per pound. (Ref. 2.29).	Obtain pilots comments on: 1. breakout forces large enough to be objectionable and to make small precise control application difficult. 2. sensitivity which makes it difficult to avoid persistent amplitude oscillations. 3. pilot-induced oscillations of a divergent nature.	In an examination of the overall system response in the two test flight conditions, the dynamic normal acceleration response of the airplane to stock force appeared to be the critical factor in the pilot's choice of control system dynamics.

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
F86E (NASA-Ames)	1957-59	Servo actuation of the ailerons and the rudder provided artificial variation of some of the lateral and directional aerodynamic stability parameters. Three modes of aileron and stabilizer system operation were available to the pilot. 1. normal control, 2. position servo (fly by wire), 3. variable stability. Stability derivatives ranges were as follows: C_{n_β} 0.510 to -0.305 C_{n_r} 1.15 to -1.53 C_{n_p} 0.121 to -0.200 $C_{n_{\delta_a}}$ 0.180 to -0.142 C_{l_β} 0.430 to -0.625 C_{l_p} 0.22 to -1.10 $C_{l_{\delta_r}}$ 0.176 to -0.152 (Ref. 2.30)	Basically this aircraft was used to determine the acceptable lateral oscillatory damping in the landing approach with emphasis on the emergency condition of damper failure.	Three regions of lateral oscillation characteristics were defined and investigated: 1. long period $3.11 \leqslant P \leqslant 4.32$ sec and moderate-roll-yaw coupling $0.49 \leqslant \lvert\phi/V_e\rvert \leqslant 0.70$ 2. long period $2.75 \leqslant P \leqslant 6.9$ sec and high roll-yaw coupling $0.93 \leqslant \lvert\phi/V_e\rvert \leqslant 1.65$ 3. short period $1.54 \leqslant P \leqslant 2.38$ sec and moderate roll-yaw coupling $0.45 \leqslant \lvert\phi/V_e\rvert \leqslant 0.63$.

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
F101A (NASA-Langley WADD)	1957-60	This vehicle was to provide the test engineer with the flexible features of a general purpose computer, coupled with those of a variable stability airplane. The airborne analog computing equipment was to be used in flight research programs to solve in real time certain sets of differential equations to provide control information to the aircraft. Inputs to the computer system as a whole were to come from the airplane motion and flight sensors, from the problem input equipment and from the pilot.	Some of the planned uses for this aircraft were roll requirements for blast escape and tracking. artificial stability for roll coupling, roll limiting and 'G' limiting schemes, control stick steering, adaptive servo and other new techniques, study of negative stability augmenters, problems of unconventional bombing techniques and studying problems of advanced vehicles along portions of their trajectories.	Not flown
F7U-3 (Navy-Cornell)	1958-59	A large vertical canard control surface was used to generate the required yawing moment to prevent the uncontrolled motions experienced at high angles of attack in the region of reduced stability, a $\dot{\beta}$ feed back loop was used to control this surface. (Ref. 2.31).	Determine a means of preventing large uncontrolled motions using automatic control.	In symmetrical stalls the motions were very mild; when large aileron and rudder deflections were applied at the stall, the airplane did little more than roll.

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
HUP-1 (Princeton)	1958-60	A standard Minneapolis-Honeywell E-12 autopilot was installed in this helicopter to provide for variation of dihedral effect, static directional stability, roll damping and yaw damping. The rolling convergence root held approximately constant at a value $\lambda_2 = -6.68$. Spiral mode damping varied from +0.15 to -0.85 and the dutch roll damping ($1/C_{1/2}$) varied from 0.5 to 7.8. (Ref. 2.33).	Conduct a pilot evaluation of carefully selected stability configurations to provide pertinent commentary and numerical ratings which could be related to known dynamic characteristics.	Analysis of test results indicated a number of areas of importance in helicopter lateral handling qualities. Specifically it was found that the dutch roll oscillation should be well damped; positive spiral damping is desirable, and, in fact, required if dutch roll damping is light, steady state control deflections should not be required to make turns after completion of the entering transients.
F-100C (NASA-Ames)	1958 to present	The following derivatives will be variable. Longitudinal-Directional-Lateral C_{m_α} C_{n_β} C_{l_β} C_{m_q} C_{n_r} C_{l_r} $C_{m_{\delta_s}}$ C_{n_p} C_{l_p} $\delta Fs/\delta f_s$ $C_{n_{\delta_a}}$ $C_{l_{\delta_a}}$ $C_{n_{\delta_r}}$ $C_{l_{\delta_r}}$ Estimates based on perfect servos indicate the following characteristics will be available at 15,000 ft	This aircraft will be used as a backup for ground simulator work. Picking up points where it is felt motion cues are important.	None as yet.

<table>
<tr><th>Type Aircraft</th><th>Date</th><th colspan="4">System Description</th><th colspan="2">Project-Purpose</th><th>Accomplishments</th></tr>
<tr><td>F-100C (Cont'd)
(NASA-Ames)</td><td></td><td><i>Mode</i></td><td><i>Char</i></td><td><i>Max</i></td><td><i>Norm</i></td><td><i>Min</i></td><td><i>Mach</i></td><td></td></tr>
<tr><td></td><td></td><td>Lateral</td><td>ω_d</td><td>0.95cps</td><td>0.59cps</td><td>0cps</td><td>0.9</td><td></td></tr>
<tr><td></td><td></td><td></td><td>I_d</td><td>1.0</td><td>0.13</td><td>-0.80</td><td>0.65</td><td></td></tr>
<tr><td></td><td></td><td></td><td>$|\phi/\beta|$</td><td>24.0</td><td>2.00</td><td>0.40</td><td>0.80</td><td></td></tr>
<tr><td></td><td></td><td>Longitudinal</td><td>ω_{s_p}</td><td>2.5cps</td><td>1.5cps</td><td>0cps</td><td>1.1</td><td></td></tr>
<tr><td></td><td></td><td></td><td>$I_{s.p.}$</td><td>0.85</td><td>0.30</td><td>-2.0</td><td>1.1</td><td></td></tr>
<tr><td>D-18
(NASA)</td><td>1959-60</td><td colspan="4">The control surface modifications consisted of a main trailing-edge flap which was connected to the aileron for maximum lift-changing capability, a short auxiliary portion of the elevator to counteract the wing pitching moment caused by deflection of the main wing flap. (Ref. 2.34).</td><td colspan="2">To provide an automatic control system capable of varying static longitudinal stability and lift curve slope. An investigation of positive and negative static longitudinal stability coupled with various effective lift-curve slopes.</td><td>Pilot opinions and flight results of an investigation at relatively low values of normal acceleration per degree change in angle of attack indicate that the upper tolerance limit of unstable static stability of the airplane (C_{m_α}) is between 0.10 and 0.16.</td></tr>
<tr><td>F-11F-1-F
(NASA)</td><td>1960-61</td><td colspan="4">An adjustable feel system connected to the longitudinal control system of a transonic fighter airplane. Variable control feel including response feel is provided from the following five sources: control position, control rate, normal acceleration, pitching velocity, and pitching acceleration. (Ref. 2.39).</td><td colspan="2">Provide a means whereby a thorough study could be made of the effects of large amounts of response feel and the stability of airplane and control system response modes.</td><td>Flight tests indicate that: (1) at the frequency of the short period mode, large amounts of normal-acceleration feel cause the control system to oscillate and excite the airplane short period mode at the same frequency. (2) The pitching acceleration component of feel is almost equivalent to viscous damping on the stick. A large pitching acceleration component excites an oscillation of the control system.</td></tr>
</table>

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
X-14 (NASA-Ames)	Sept 60 to present	The Bell X-14 aircraft has been modified with the addition of a more powerful engine and a secondary automatically controlled jet control arrangement to permit its use as a variable stability airplane. The following moments can be obtained:	The purpose of this aircraft is to investigate hovering and transition, etc. for VTOL work.	None

ESTIMATED MAXIMUM EFFECTIVENESS

Axis		*Manual*		*Augmented*
Roll L_δ	rad. sec.	1.9	+	1.72
Pitch M_δ	rad. sec.	0.95	±	0.86
Yaw N_δ	rad. sec.	0.54	+	0.48

Type Aircraft	Date	System Description	Project-Purpose	Accomplishments
Helicopter (Natl Rsch Council - Canada)	1961	A system is proposed for the use of a helicopter tethered to a ground computer to simulate VTOL aircraft handling qualities.	Obtain VTOL handling qualities under motion stimulus.	None
YHC-1A	1961	This new type helicopter which has sufficient space for an adequate payload is being fitted with improved variable stability equipment which will permit simulation not only of control power and angular velocity damping but also variations of static stability. During initial use additional equipment will be installed when feasible. This could include items such as methods of providing time lag in controls. (Ref. 2.41).	Stability and control and handling qualities tests of VTOL aircraft.	

APPENDIX II

F/C SYSTEM GROUND SIMULATORS

Title	Location	Description	Reference or Reports	Comments
'g' seat	NASA-Langley	Vertical translation and pitching degrees of freedom. For evaluation of low altitude flight characteristics.	NASA TM X-420	
'g' seat	North American Aviation, Columbus, Ohio	Subjects pilot to variable vertical acceleration similar to ride through turbulence. Vertical translation and pitching degrees of freedom. Similar to NASA-Langley 'g' seat.		
'g' seat	Convair, Ft Worth, Tex.	Simple simulator used to simulate jolting ride at low altitude, scope display.		Low-altitude flight studies
'Iron' Cross control simulator	NASA, HSFS Edwards AFB, Cal.	Three degrees of freedom, roll, pitch and yaw. Used to investigate pilot control with jet reaction devices.		
'Iron Horse'	Boeing-Seattle	Reaction control simulator using on off jets on 3-degree-of-freedom structure.		
Control systems simulator	Chance Vought, Dallas, Texas	Structure supported by air bearing. Reaction controls inertia wheels - will accommodate a pilot.		
Floated table	NASA-Ames	Air supported table for investigation of space control systems.		
Roll-pitch chair	NASA-Ames	Two axis rotation moving simulator display and controls provided.	NASA Memo 1-29-59A	

Title	Location	Description	Reference or Reports	Comments
Pitch-roll	NASA-Langley	General purpose angular motion simulator free in pitch and roll.		
Spin-chair	AF School of Aviation, Medicine, Brooks AFB, Tex.	Rotatable chair electronically controlled for study of pilot reactions and disorientation.		
3 Degree of freedom	NASA-Ames	Gas bearing, 360° rotation possible in 3 axes provided with cockpit and controls.		Designed
2 Degree of freedom simulator	NASA-Ames	Any two degrees of rotation possible.		
3 Degree of freedom reaction control simulator	NASA-Ames	Air bearing supported structure to investigate reaction - pilot characteristics. Variable inertia possible.		
6 Degree simulator	NASA-Ames	6 degree of freedom simulator having limited travel for V/STOL and transport landing studies.		Being designed
5 Degree Simulator	NASA-Ames	Roll-pitch-yaw carriage free to heave, installed on a centrifuge.	Aviation Week Sept 12, 1960	Being constructed
V/STOL landing simulator	NASA-Ames	Landing Approach Simulator having 120 ft of vertical travel, constructed on outside of 40 ft x 80 ft wind tunnel.		Proposed
Visual Projection Facility	NASA-Ames	Projection facility to simulate horizon stars or landing approach situation. Can be used with other simulators.		

Title	Location	Description	Reference or Reports	Comments
Space Rendezvous simulator	NASA-Langley	Large 6-degree-of-freedom simulator installed in a hangar.		Designed for space rendezvous but useful for V/STOL studies.
MASTIF multiple-axis test inertia facility	NASA-Lewis	Four gimbals to simulate yaw, roll and pitch angles. Installed in altitude wind tunnel--altitude and temperature factors of space flight can be simulated. High spin rates possible.	Aviation Week Nov 30, 1959	Used for reaction control and Mercury Capsule studies.
Motion simulator	Grumman Aircraft Eng. Co.	Free in roll, pitch and heave - 3 'g' acceleration limit, instrument display and also provided with external display for VTOL and approach and landing simulation.	Grumman Reports	Particularly useful for approach and low-altitude studies.
Space vehicle pilot simulator	General Electric Missile & Space Vehicle Dept.	9 ft x 12 ft room accoustically insulated bordered by large computer-programmer observation area. Vehicle characteristics simulated. Simple seat-control-display setup used.	WADD TR 60-695 Part I and Part II	
Visual space flight simulator		Theatre containing full scale space vehicle cabin plus separate studios where closed circuit TV presentations will be originated for projection on windows.	Aviation Week Feb 6, 1961	Proposed facility under study by Bell Aerosystems Company
Space flight simulator	Chance Vought, Dallas, Texas	3-axis motion compartment. External display on 20 ft sphere surrounding cockpit, enclosed in space environmental conditions simulator, heat, noise, vibrations, pressure, temperatures, radiation and meteoritic impact. Digital computer used to simulate flight mechanics equations.	Vought Report ADB 1-4	In construction

Title	Location	Description	Reference or Reports	Comments
STOL control simulator	Boeing, Wichita, Kansas	A-six-degree-of-freedom STOL flight simulator to examine handling qualities, flight control and display.		
Control simulator	Bell Helicopter, Dallas, Texas	6-degree-of-freedom simulator - load capacity of 1000 lb. 5 cycles/second in pitch, roll and yaw.		Particularly useful for helicopter and V/STOL studies.
Rotation simulator	AF School of Aviation Medicine	3-degrees-of-freedom, roll, pitch, yaw. 10 ft sphere on air bearing. Pilot can operate jets or reaction wheels. Pilot display, perturbations, can be introduced. Pressure can be simulated 50 r.p.m. in one axis, 70 r.p.m. resilliant.		
VTOL simulator	Norair	3-degrees-of-freedom, roll, pitch, yaw. V/STOL simulator.		
T-37 general purpose F/C simulator	WADD	Modified T-37 operational simulator free in pitch and roll with washout in motion to simulate continuous rolling. Used for instrument and display concept research.		
Flight acceleration simulator	Naval Air Development Center, Johnsville, Pa.	Centrifuge combined with piloted capsule with two degrees of freedom.		
3-Degree of freedom reaction control simulation	NASA-Ames	Air bearing supported structure to investigate reaction - pilot characteristics. Variable inertia possible.		

Title	Location	Description	Reference or Reports	Comments
V/STOL simulator	Chance Vought, Dallas, Texas	Fixed base - hydraulic stick and rudder-feel extensive display.	IAS Paper 6-60	
Visual display simulator	NASA-Langley	Landing approach visual display simulator.		
Mark IV space cabin simulator	Lear, Grand Rapids, Michigan	Fixed base, elaborate display, space cabin simulator.		
Project Mercury trainer	NASA-Langley	Manned satellite trainer - link to computer for animated display to provide training in cockpit procedures.	Aviation Week Feb 20, 1961	
T-33 ground simulator	Cornell Aero Lab., Buffalo, New York	T-33 Variable-Stability-Airplane used as fixed base ground simulator by use of computer to simulate dynamic equations.		
General-purpose flight simulator	Convair, Ft Worth, Texas	Fixed base, elaborate instrument display plus projection, external viewing.		Particularly useful for low altitude flight simulation
Carrier landing simulator	Douglas, El Segundo, California	Fixed base simulating mirror landing approach system.		
ANIP simulator	Douglas, El Segundo, California	Fixed base - investigation of advanced display concepts.		
General purpose simulator	NASA, Edwards AFB	Fixed-base, cockpit simulator, 200 amplifier computer.		

Title	Location	Description	Reference or Reports	Comments
F-102 general purpose simulator	WADD	Elaborate fixed base simulator to evaluate new display and instrument concepts.		
Aerospace simulator	AFMTC, Cape Canaveral, Fla.	Aerospace profile simulator for pilot training and integration of pilot with ground crew.		To be built
Pilot training simulator	AFFTC, Edwards AFB, Calif.	Simulation oriented to air launch phase of advanced vehicles for pilot training.		To be built
Visual flight simulator	North American Aviation, Columbus, Ohio	Fixed base, V/STOL simulator with television presentation free in 6-degree-of-freedom projecting terrain picture.	IAS, Crone & O'Harrah	Used for V/STOL studies
Fixed-base orbital flight simulator	Chance Vought, Dallas, Texas	Fixed-base, elaborate cockpit with 560 amplifier analog computer plus digital computer to simulate six-degree-of-freedom flight mechanics and equations for orbital and space navigation.	Vought Report ADB 1/4	Particularly useful for orbital flight, rendezvous and reentry studies.
'Humming Bird' VTOL simulator	Lockheed, Marietta, Ga.	VTOL tethered rig using jet engines to evaluate VTOL handling qualities and flight control.		Other tethered rigs have been used (X-13, Avro machine, etc) to check specific designs.

NOTE: The above listing does not include the class of fixed base simple cockpit-computer simulator. There are literally scores of these simulators of varying degrees of simplicity in government and industry. Some fixed-base simulators of rather elaborate or unusual nature are included. Also not included is the class of fixed-base simulators used in the development of the flight control system of a given vehicle, the 'iron bird' simulators. It is quite probable that there are simulators in existence or planned that should be added, however, and any information on such simulators would be appreciated.

APPENDIX III

MAJOR ENVIRONMENTAL SIMULATORS

Title	Description	Location	Comments
Null gravity simulator	Simulates zero g's by spinning a man submerged in a fluid	Lockheed, Marietta, Georgia	
Zero g's	C-131 B simulates zero g's for approximately 12 to 15 seconds	WPAFB	
Zero g's	KC-135 simulator zero g's for over 30 seconds	WPAFB	
Johnsville human centrifuge	50 foot arm, 4000 hp motor, the gondola is gimbaled	Aviation Medical Acceleration Lab.	
Human centrifuge	The centrifuge is driven by an automobile engine that winds up an eighteen ton flywheel	U. of Southern California	
Whirler	40g gimbal-mounted gondola centrifuge	Navy's Aviation Medical Acceleration Lab.	
Variable-climate chamber	Temperature range of -100° to $170^{\circ}F$	Boeing, Seattle	
Climatic hangar	Temperatures as low as $-65^{\circ}F$	Eglin AFB	Entire aircraft may be taken into chamber.
Rocket sled	20,000 foot track	Edwards AFB	Vehicles have reached Mach 2 on track
Rocket sled	12,000 foot track	Hurrican Mesa	

Title	Description	Location	Comments
Rocket sled	30,000 foot track	Holloman AFB	
Crash sled	Acceleration: 0 - 57 g's Track length: 2000 ft Velocity: 150 m.p.h.	Edwards AFB	
Space simulator	Minimum friction bearing	Boeing, Seattle	Checks attitude control systems of space vehicles
3-axis simulator	Single air bearing table can support 1000 lb load	Grumman	Used to test control equipment
Boeing test chamber	-85 to 1200°F; up to 120,000 ft Dimensions 19 ft diameter x 35 ft long	Boeing	
Whirlee	Gondola for spin tests with a pressure altitude capability of 60,000 ft and a maximum temperature of 110°F.	Navy's Aviation Medical Acceleration Laboratory	
Altichamber	Environmental chamber with capabilities of 100,000 ft, -100 to 165°F, and relative humidity of 15 to 95%	McDonnell Aircraft	
Martin torture chamber	Environmental chamber with capabilities of ice and snow, 100,000 ft altitude, -100° to 165°F, simulated desert sand and dust storm, 95% humidity, tropical rain, fungus, salt spray, and vibration	Martin Aircraft	
Tenney simulator	45 mile altitude capability	Cape Canaveral	Project Mercury high altitude simulation

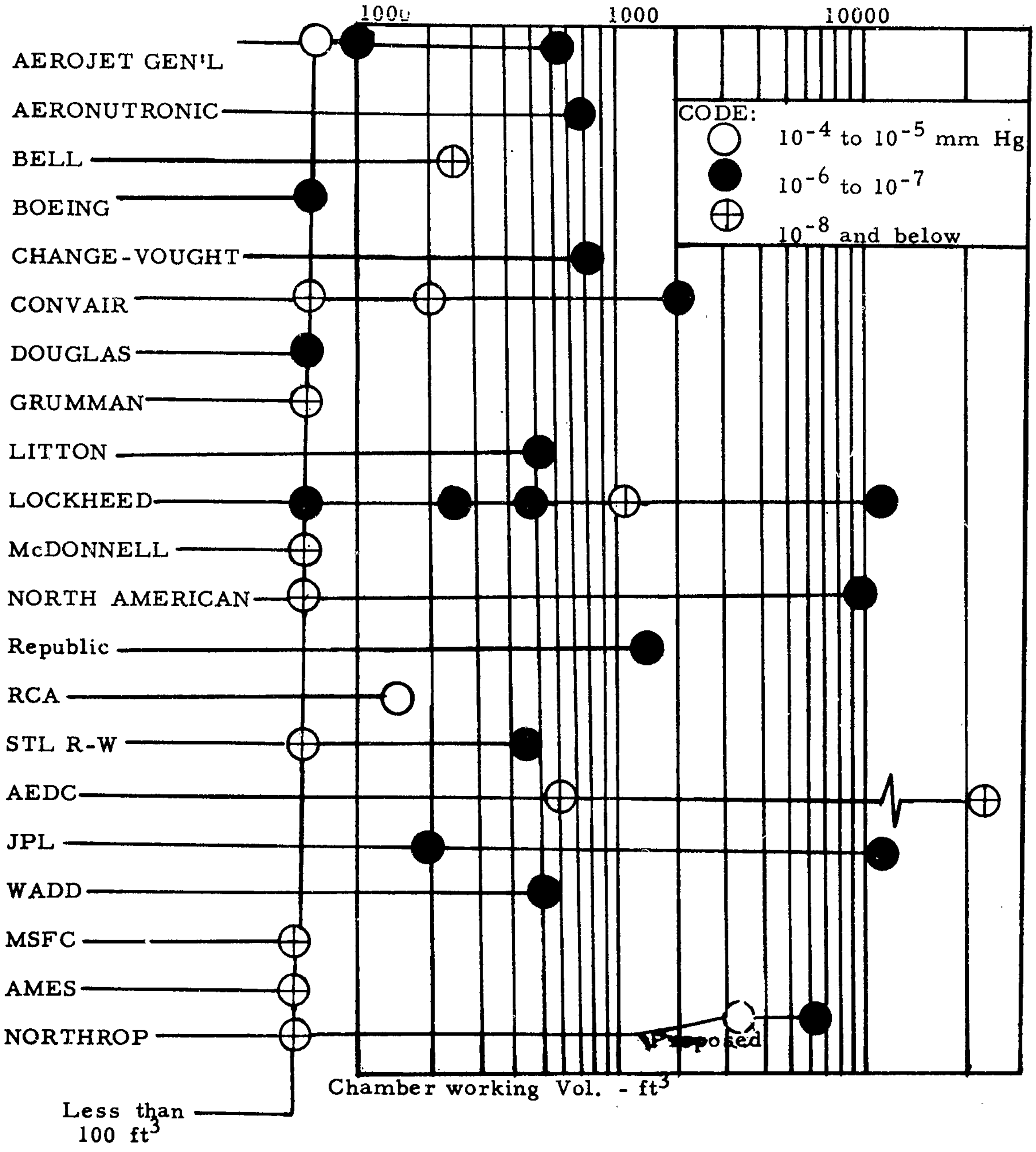
Title	Description	Location	Comments
Space environment simulator	Altitudes up to 200 miles and temperatures to -320°F and will duplicate sun's radiation spectrum.	Chance Vought Corporation, Astronautics Div.	It is planned to incorporate provisions for bombarding test articles with meteorite like particles.
Dynamic analyzer	Vibration: Simultaneous 3-Direction 1/2 c.a. to 5 g to 800 cps. Ozone; Extended capability. Magnetic Fields; Extended capability. Altitude: 3.8 x 10^{-7} mm Hg Temperature: -90 to 500°F	WADD	
Hyper-environmental centrifuge	Vibration: (Sinusoidal) Frequency: 5 to 2000 cps: Magnitude: 50g (Random): 5 to 2000 cps: Magnitude: 0.2 g's/cycle/sec Shock: 0 to 100 g's over 4 to 10 milliseconds Acceleration: 0 to 300 g's in 3 min Altitude: 200,000 ft Temperature: -300 to 1000°F	Undetermined	$300,000,000 estimated cost
Mark II space facility	Solar Radiation: Intensity: 130 watts/ft^2 Spectrum: Simulated sunlight Vibration: Random: 0 to 3500 cps, 5000 lb Albedo: As required Altitude: 650,000 ft approx Low Temperature: -315°F Size: (Test space internal) 30 ft diameter x 70 ft high	Undetermined	
Lockheed simulator	Altitude: 200 mile capability 100 Btu/sq ft/hr and temperature at walls of chamber -320°F	Lockheed, Sunnyvale, Calif.	Can accommodate an eight foot diameter satellite, 15 ft long

Title	Description	Location	Comments
Project heat	High temperature test cell 7.5 million watts of radio frequency energy in 100 sq ft area for re-entry heating studies.	WADD	
Nuclear explosion effects	Designed to study effects of nuclear explosions in space.	AFSWC	To be built
Sun simulator	Lamps, filters, optical system and programmed control accurately simulates sun's direct and reflected radiation.	Bausch & Lomb Inc. Rochester, N.Y.	
Air bearing table	Three axis table to check control systems up to 1000 lb.	Grumman	
Environmental chamber	Altitude 0 - 225,000 ft -100°F to 200°F localized heating to 1000° 5 to 95% relative humidity vibration exciter 5 to 2000 cps	AF Missile Development Center, Holloman AFB, N. Mexico	
Space cabin simulator	8 ft x 12 ft space cabin to simulate cabin environment including closed 1 cycle.	School of Aviation Medicine, Brooks, AFB	
Space environment facility	18 ft x 22 ft chamber, -65 to 160°F, 180 ft altitude.	WADD	To be modified to 2.4 million attitude 2400°F -423°F, solar radiation.
Moment of inertia platform	Large platform able to oscillate 300,000 lb aircraft or missile at low frequencies, all three axes. Precisely controlled by servo system.	AFFTC	

Title	Description	Location	Comments
Space simulator	Altitude: 10^{-9} mm Hg Wall Temperature: -382°F Ozone: As needed Shock: 35 g to simulate staging 2-5 g to simulate rendezvous docking Size: 32 ft diameter by 54 ft high	Valley Forge Research Facility, Philadelphia General Electric, MSVD	
Lunar housing simulator	Simulates lunar living conditions including ecological systems for humans, animals and plants	Martin - Denver	
Snap environmental test facility	Allows full-power nuclear operation of snap-powered vehicles		
Zero G's	Simulates zero g's for approximately 90 seconds, F-104B aircraft	Edwards AFB, Calif.	
Human centrifuge	Open cabin centrifuge, arm approximately 20 ft, has gone up to 16 g's	WADD	
Parachute test tower	A whirling tower and has been used to test escape capsule	El Centro, Calif., AFFTC facility on Navy Base	

NOTE: On the following page is a chart showing some of the environment chamber facilities available, in addition to those listed above.

ALTITUDE CAPABILITIES OF SPACE SIMULATION FACILITIES
1960-62



Reference: AIA Report on "A Survey of Space Hyper-Environmental Facilities"

Altitude Capabilities of Space Simulation Facilities 1960-62

APPENDIX IV

LISTING OF AIR FORCE AIRCRAFT FOR WHICH OPERATIONAL FLIGHT TRAINERS WERE BUILT

B-47 b

B-47 e

B/RB-58 A

B-66 b

R/B-66 B

B-52 D

B-50

B-36

B-57

B-52 B

B-52 F

B-52 G

C-97 A

KC-97 G

C-118 A

C-119 C

C-119 G

C-121 C

RC-121 D

C-124 A

C-124 C

C-130 A

C-130 B

C-131 A

C-133 A

KC-135

F-86 D

F-86 L

F-89 D

F-89 H

F-100 A

F-100 C

F-100 D

F-101 A

RF-101 A

F-101 B

F-102 A 4 types

F-106 A

F-105

APPENDIX V

LARGE DIGITAL COMPUTATIONAL FACILITIES IN AIRCRAFT INDUSTRY

Machines	Aircraft Company	Location
Rand 1103A IBM 7090 IBM 704	Boeing Airplane Co., Aero-space Div.	Seattle 24, Washington
IBM 7090	Boeing Airplane Co., Transport Div.	Renton, Washington
IBM 709	Boeing Airplane Co.,	Wichita 1, Kansas
IBM 704	Convair-Astronautics	San Diego 12, Calif.
IBM 704	General Dynamics Corp. Convair Div.	Fort Worth, Texas
IBM 709 IBM 7090	Lockheed Aircraft Corp., Calif. Div.	Burbank, Calif.
IBM 704 IBM 7090	Convair - San Diego	San Diego 12, Calif.
IBM 704 IBM 7090	Convair - Fort Worth	Fort Worth, Texas
IBM 704	Chance Vought Aircraft Company	Dallas 22, Texas
IBM 704	Douglas Aircraft Corp. El Segundo Div.	El Segundo, Calif.
IBM 704	Douglas Aircraft Corp. Testing Div.	Santa Monica, Calif.
IBM 704 IBM 709 IBM 7090	Douglas Aircraft Corp. Missiles & Space Dept.	Santa Monica, Calif.
IBM 709	Douglas Aircraft Corp. Santa Monica Div.	Santa Monica, Calif.
IBM 704	Grumman Aircraft	Bethpage, L.I., N.Y.
IBM 704 IBM 7090	Lockheed Aircraft Corp.	Marietta, Georgia
IBM 704 IBM 709	Hughes Aircraft Company	Culver City, Calif.
IBM 709 IBM 7090	McDonnell Automation Center	St. Louis 66, Missouri

Machines	Aircraft Company	Location
IBM 709	The Martin Company	Baltimore 3, Md.
IBM 704 IBM 7090	Martin Co., Denver Div.	Denver 1, Colorado
IBM 709	The Martin Co.	Orlando, Florida
Rand 1103A IBM 709 IBM 7090	Lockheed Aircraft Corp. Missiles & Space Div.	Sunnyvale, Calif.
IBM 709 IBM 7090	North American Aviation, Los Angeles Division	Los Angeles 45, Calif.
IBM 704 IBM 709	North American Aviation Columbus Division	Columbus 16, Ohio
IBM 704 IBM 7090	Northrop Corporation Norair Div.	Hawthorne, Calif.
IBM 704 IBM 709	North American Aviation, Inc. Rocketdyne Division	Canoga Park, Calif.
IBM 7090	North American Aviation, Autonatics Div.	Downey, Calif.
IBM 704	Pratt and Whitney Aircraft	United, Florida
IBM 704 IBM 709	Republic Aviation Corp.	Farmingdale, N.Y.
IBM 704	Temco Aircraft Corp.	Dallas, Texas
IBM 704	United Aircraft Corp.	East Hartford 8, Conn.

APPENDIX VI

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ADDENDUM

AGARD SPECIALISTS' MEETING
on
STABILITY AND CONTROL

Complete List of Papers Presented

Following is a list of the titles and authors of the 41 papers presented at the Stability and Control Meeting held in Brussels in April, 1960, together with the AGARD Report number covering the publication of each paper.

INTRODUCTORY PAPERS

The Aeroplane Designer's Approach to Stability and Control, by G.H.Lee (United Kingdom)	Report 334
The Missile Designer's Approach to Stability and Control Problems, by M.W.Hunter and J.W.Hindes (United States)	Report 335

DESIGN REQUIREMENTS

Flying Qualities Requirements for United States Navy and Air Force Aircraft, by W.Koven and R.Wasicko (United States)	Report 336
Design Aims for Stability and Control of Piloted Aircraft, by H.J.Allwright (United Kingdom)	Report 337
Design Criteria for Missiles, by L.G.Evans (United Kingdom)	Report 338

AERODYNAMIC DERIVATIVES

State of the Art of Estimation of Derivatives, by H.H.B.M.Thomas (United Kingdom)	Report 339
The Estimation of Oscillatory Wing and Control Derivatives, by W.E.A.Acum and H.C.Garner (United Kingdom)	Report 340.
Current Progress in the Estimation of Stability Derivatives, by L.V.Malthan and D E.Hoak (United States)	Report 341
Calculation of Non-Linear Aerodynamic Stability Derivatives of Aeroplanes, by K.Gersten (Germany)	Report 342

AEROELASTIC EFFECTS

COUPLING PHENOMENA

STABILITY AND CONTROL AT HIGH LIFT

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THE USE OF SIMULATORS

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629.13.014.7

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In this Report a review is made of the simulation facilities commonly used in the United States. An attempt is made to classify these facilities and to understand how and why they are needed and came into being, and how they are used. An indication of the use of flight control system simulators in the design of a vehicle in the United States is given. Some thoughts on the philosophy of use of simulation are offered and conclusions presented.

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